THE SNOWY RIVER: A MATURE BARRIER ESTUARY

J. B. HINWOOD[1] & E. J. MCLEAN[2]

[1]Department of Mechanical Engineering, Monash University, Clayton, Victoria 3168, Australia
[2]Department of Land and Water Conservation, Wollongong, New South Wales 2500, Australia

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The 1989 environmental study of the Snowy River estuary is described, with some data from later surveys. The study encompassed hydrodynamics, geomorphology and benthic ecology. The estuary is a largely infilled embayment, receiving substantial fresh water and sediment inflows. The present channels and mouth are formed by floods of return period 5 or more years, with limited reworking by tidal currents, the currents in the salt wedge being too weak to move sand. Longshore drift gradually closes the entrance, reducing the tidal prism. Channel sediments are predominantly fluvial sands, with some marine sands, and silts in the tidal lagoons. Zones with characteristic geomorphological regimes were defined.

Maximum salt penetration into the estuary occurs under conditions of low river inflow and large entrance depth. The data gathered under these conditions identified a range of hydrodynamic and salinity regimes present in the estuary, from well mixed to salt wedge. The range of conditions was extended by use of a numerical model. The relationship between the biota present and the hydrodynamic and geomorphological zones was demonstrated.

THE SNOWY RIVER is one of Australia's largest rivers and has great economic and conservation values. In 1965 the Snowy Mountains Scheme (SMS) commenced diversion of water from part of the catchment, affecting low flows particularly. Over the last 15 years there have been development proposals for the region, such as wood chipping plants, which would require the export of water from the Snowy River. Other concerns related to the 'minimum ecologically sustainable river flow' have led to recommendations to change the regime of water releases from the SMS.

While the riverine reaches of the Snowy River are now receiving their due attention, the estuarine reaches have only been studied comprehensively in one study (Hinwood et al. 1989; hereafter referred to as HWMP). In this paper we review the knowledge of the estuarine system, describe the main findings of the 1989 survey, and present some results of more recently conducted surveys and numerical modelling.

To assess the impacts of proposed developments or management strategies is a complex task. Simplifications can be achieved by identifying estuarine reaches with characteristic features which will then show similar responses and which may be compared more readily with previously studied estuaries. The features considered here are based on geomorphology and hydrodynamics, which together determine the nature of the habitats and hence the biota present.

Following a general description of the Snowy River estuary in the next section, in section 3 the data collection of HWMP is outlined. A kinematic and transport model of the water movement and salinity distribution under conditions of low to moderate flow was developed on the basis of this study (Hinwood & McLean 1992) and some results are given in section 5. These data, model results and data from unpublished reports are used to classify the hydrodynamic and sedimentological regimes of the principal estuarine segments.

THE SNOWY RIVER ESTUARY: GENERAL DESCRIPTION

The Snowy River rises in the Great Dividing Range in southeastern New South Wales. It flows generally southward, entering the Tasman Sea on the north-eastern coast of Victoria. The catchment of the Snowy River is approximately 13 700 square kilometres in area, most of which is uninhabited, forested gorge country. For the last 24 kilometres to the coast the river passes through rich alluvial flats which are subject to periodic inundation by the river (see Fig. 1). The much smaller Brodribb River joins the Snowy River a few kilometres from the sea via the tidal Lake Curlip just upstream from the town of Marlo. Closer to the sea, Corringle Creek enters, via the tidal Lake Corringle. Corringle Creek carries only local and flood drainage.

The maximum water depth in the lower estuary at Marlo is about 5 m at mean tide (MWL) falling to 3.3 m at First Island and shoaling upstream.

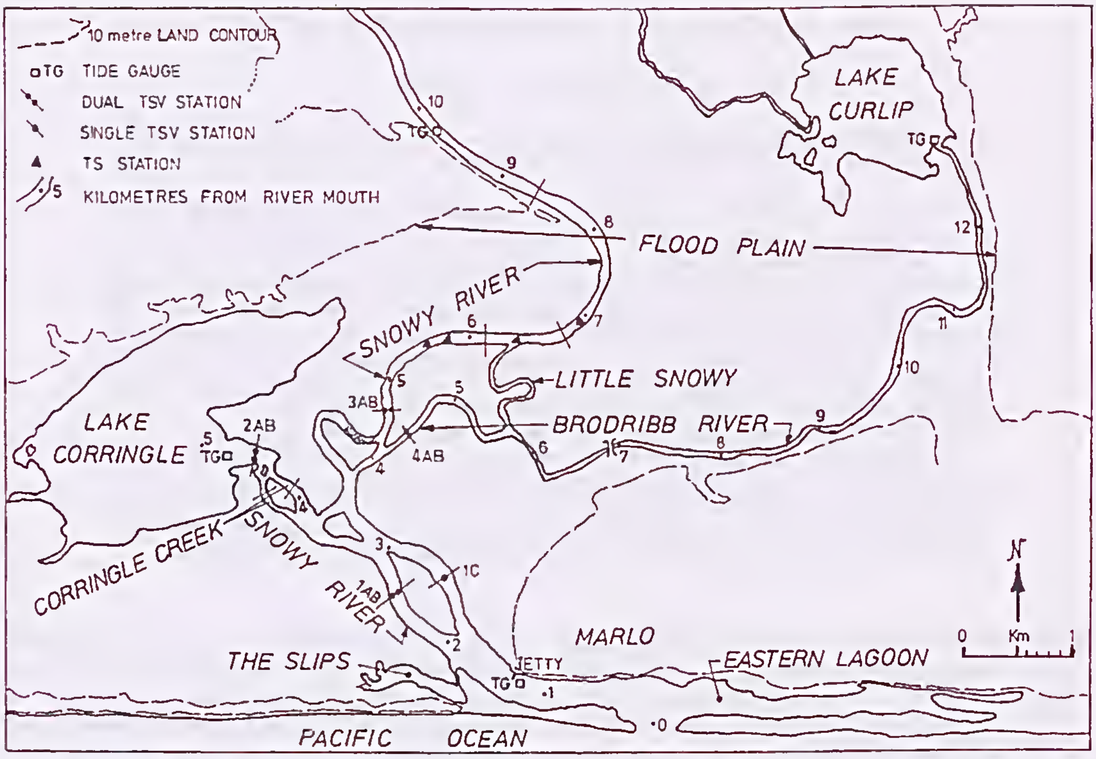

Fig. 1. Snowy River estuary showing data collection sites of HWMP. Δ = Temperature and salinity; —•—IC = velocity profiles; TG = tide gauge.

Deep scour holes have formed at the outside of bends (4–6 m at MWL) with point and crossover bars as shallow as 1 m. Lake Curlip has a maximum depth of 2 m and a mean depth of 1 m, while Lake Corringle has a maximum depth of 1.4 m at its mouth and a mean depth of 0.7 m.

While rainfall is distributed throughout the year, it is heaviest from May to December, in particular in September and October. The driest months are January to March, although periods of low flow may occur at any time throughout the year and some of the highest flows on record have occurred in these typically drier months. From 1965 the runoff from about 15% of the catchment has been captured by the Snowy Mountains Scheme (SMS) and diverted out of the catchment. Despite the small area, the loss of this run off has reduced typical and dry weather flows, the latter quite significantly (James 1989; Dr C. Gippel 1998, pers. comm.). Fig. 2 (after James 1989) shows the percentage of observations for which a given monthly mean flow is exceeded pre- and post-SMS. The curves differ by a factor of about 4 most of the time, but converge for occurrences <3%, ie. for months in which large floods occur. All hydrographic statistics used here are for post-SMS conditions.

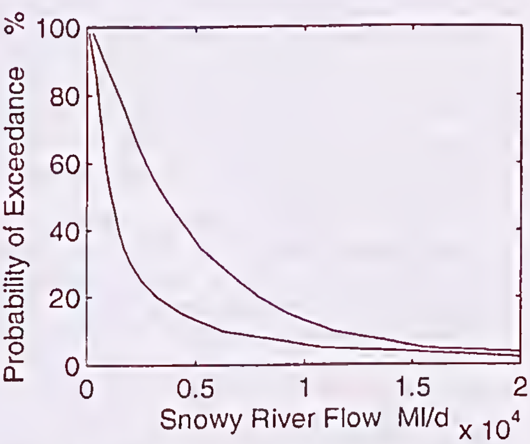

Fig. 2. Snowy River—flow-duration analysis for monthly-mean flows at Jarrahmond (James 1989). Upper line pre-SMS; lower line post-SMS.

The coast at the mouth of the Snowy River trends east–west and is exposed to waves from the sector east-south-west. Because of the limitations of fetch, extreme storm waves are likely to result from southeasterly storms, but the greater frequency of storms from the south-west leads to a dominant sand transport from the west towards the east. At nearby Lakes Entrance, the first author has previously calculated the same pattern with a net west to east transport in the order of 100 000 cubic metres of sand per year which he confirmed from dredging records at the entrance.

Cross-sections of the tidal Snowy, upstream of the Little Snowy River, from 1936 to 1988 (Rural Water Commission 1988; hereafter referred to as RWC) show the generally stable and regular form of the river channel. Bed sediment analyses at several stations show that the bed is predominantly sand with a median diameter falling from medium sand near Orbost (18 km from the mouth) to fine sand near Marlo (2 km from the mouth).

Except for the rare occasions when the entrance to the sea is closed, tides penetrate the estuary as far upstream as Orbost. At times of low to moderate river discharge the ebb and flood flows provide the dominant water movement in the estuary. At these times, salt water from the sea penetrates inland about 8 km but is believed to penetrate very much further under drought conditions. At times of fresh or flood flows in the Snowy River, the river flow dominates, particularly in the upstream reaches.

The entrance, which from time to time is scoured by flood flows, is closed progressively by longshore sand movement. Tidal flows into and out of the estuary are restricted by this reduced entrance section, thus reducing the intensity of tidal mixing in the estuary. The conditions of moderate river flows, relatively large channel cross-sections and relatively weak tidal mixing are ideal for the formation of an estuarine salt wedge. A salt wedge is observed under dry-weather river flow conditions in the upper part of the Snowy River estuary but a more complex hydrodynamic regime occurs in the lower part of the estuary, due to flows into and out of the two major branches—the Brodribb River and Corringle Creek.

THE SNOWY RIVER SURVEY

The 1989 environmental study of the Snowy River estuary conducted by HWMP has not been described in the scientific literature and results are available only in the report of the now defunct Department of Water Resources Victoria. The study was commissioned as a low cost but broad scope investigation of the estuary to identify environmental issues within the estuary and to assist staff of the department to determine the minimum environmental flow. Components of the study were hydrodynamics, geomorphology and benthic ecology.

A survey was conducted on 11 January 1989 by the principal investigators, comprising a low altitude aerial inspection of the whole estuary, a 'snapshot' of measurements of water temperature and salinity throughout the main estuary, preliminary inspection of the principal sediment deposits, and establishment of the transects for benthic sampling. The marine ecological investigations were conducted simultaneously with this survey.

An intensive collection of hydrodynamic data was undertaken from 24 to 26 January 1989. It included temperature/salinity/velocity (TSV) profiling over a tide cycle at the four sections shown in Fig. 1. Additional temperature/salinity profiles were taken in conjunction with longitudinal echo sounder profiles, which were used to identify salinity structures. Four tide recorders were deployed for the study and additional staff gauges were read opportunistically to provide information on tidal range; Fig. 1 shows stations and Table 1 shows the tidal ranges recorded on 25 January during the survey.

Parameter	Ocean tide Eden forecast	Measured Snowy River 1.3 km	Measured Snowy River 9.7 km	Measured Lake Corringle 4.7 km	Measured Lake Curlip 10.9 km
LW height (m)	0.400	0.568	0.120	0.272	0.258
LW time (hours)	0340	0540	0624	0604	0706
HW height (m)	1.400	1.283	0.777	0.937	0.894
HW time (hours)	1008	1158	1226	1330	1416
LW height (m)	0.200	0.545	0.138	0.326	0.314
LW time (hours)	1630	1922	2024	1958	2100
HW height (m)	1.000	1.062	0.545	0.711	0.668
HW time (hours)	2301	0100	0040	0142	0236

Table 1. Tidal range data, 25 January 1989 (from HWMP). Times in EST; height datum arbitrary except for Eden.

January is normally one of the driest months of the year, and this was no exception, with the Snowy River discharge falling from a flood peak of 154 000 ML/day in November 1988 to 1060 ML/day for the survey and the preceding week, while the discharge in the Brodribb River was about 140 ML/day.

SNOWY RIVER ESTUARY: GEOMORPHOLOGY AND SEDIMENTARY PATTERNS

The geological evolution of the estuary is dependent on the influx of sediment from two sources: fluvial transport from the catchment and tidal transport of nearshore sands through the tidal delta adjacent to the mouth. The latter is restricted in area because of the moderate tidal range and relatively small upstream tidal prism. The primary mechanism for supply of sediment to the estuary appears to be the flux of riverine sand and mud which accompanies fluvial flood flows. Under prolonged low river flow the entrance channel constricts due to shoals and may even close. Closures have been recorded both pre- and post-SMS.

The Snowy River estuary has formed in the former embayment caused by the drowning of the lower reaches of the Snowy and Brodribb rivers by interglacial sea levels. The coastal embayment was probably initiated during late Tertiary–early Pleistocene times when the lower sea level associated with glacial maxima caused the Snowy River to entrench (Hills 1951). Eustatic changes over the Pleistocene would have resulted in successive drowning associated with delta progradation into the embayment interspersed with incision and reworking of fluvial and marine sediments by the river during lower sea levels. The Holocene transgression which began some 17 000 to 20 000 years BP and reached its present position some 6000 years BP would, therefore, have drowned a complex embayment with remnants of previous interglacial marine and alluvial deposits modified by riverine processes during glacial phases.

The present estuary now occupies the lower sections of the former embayment with the upper section being occupied by the Snowy River flowing through an alluvial deltaic plain formed by river sediments as they prograded into the former estuarine reaches. Inter-tidal environments are largely restricted to the lower section with tidal penetration extending into the alluvial floodplain section via the main river channels of the Brodribb and Snowy rivers. Lakes Curlip and Corringle are the remnants of the much larger drowned estuary. Both lake beds comprise marine silts overlain by fresh water *Phragmites* sp. and *Melaleuca* sp. peaty deposits.

A description of the morphology of the estuary, particularly the lagoon system was given by McLennan (1972). He described cores and sediments exposed by erosion, showing that periods of deposition under both freshwater and salt water conditions had occurred in the lagoons. Over the 60 years prior to 1972 the most significant morphological changes were the colonisation of some lagoon areas by *Phragmites* and some shoaling of Lake Corringle. Both McLennan and RWC describe minor movements of the estuarine river channels, being zero at most sections, but up to 10 m in 50 years in a couple of places. Breakout of flood flows from the Snowy River channel downstream of Orbost were described by Finlayson & Bird (1989).

A Holocene barrier system, composed of sediments deposited during the last rise in sea level is located across the former bay entrance, forming a barrier estuary with a small estuarine entrance. Influx of marine water is largely by tidal flows through the constricted entrance. The entrance normally remains open, due to the occasional river floods and tidal currents generated as a consequence of the large water surface areas within the estuary. This is despite the littoral drift along the coast from west to east which causes the progressive deflection of the entrance after the floods break out, usually near Marlo. The presence of washover fans adjacent to the estuary mouth reveals another but minor mechanism of seawater input.

Data on the fluvial sediments have been collated by RWC and Brizga & Finlayson (1994). The bed sediments in the Snowy and Brodribb River estuary have been sampled by HWMP and in unpublished reports by students of the Department of Mechanical Engineering, Monash University, and the Department of Geography, Melbourne University. Data from HWMP are given in Table 2, supplemented by Monash University data from 1993 near the Lakes. (Care should be taken in combining data from different surveys as the RWC data show variation from survey to survey, eg. at Orbost d_{50} varies from 0.45 to 0.6 mm.) Sediment in the estuary is predominantly derived from the fluvial source and consists of coarse angular sand with mica and charcoal fragments in varying amounts. The percentage of mud present in the sample varies and is greatest in deeper or more protected locations where tidal currents were not able to substantially rework the sediment. Thus the bed sediments in the deeper reach at Marlo and in the tidal lagoons contained a significant fraction of mud and fine organic material. In some cases the sample included two subpopulations; fluvial sand which would have been deposited during the receding phase of the previous flood and finer material (silts and clays) transported and deposited over the sands by the tidal currents. Marine material, brought into the estuary through the entrance by tidal currents and waves, is restricted to the tidal delta. This material generally contains more rounded grains and is better sorted than the fluvial material.

There was no evidence of an increase in sediment load to the estuary in recent years nor of a change following the SMS (Brizga & Finlayson 1994), although such changes are being documented upstream of Orbost.

The estuary is in a mature stage of its geomorphological development, with broad floodplains, cutoff bays and a relatively short tidally-dominated segment. It most closely resembles the Barrier Estuary type 4c or 4d described by Roy (1984) (see Fig. 3C–D). The dimensions of the river channels are determined by flood flows and the dominance of river flow in the upper estuary is extended into the lower reaches during high seasonal discharges or individual fluvial events.

The classification of the Snowy Estuary as being transitional between Roy's types 4c and 4d has important implications for habitat and faunal diversity and temporal variability in water properties such as turbidity and salinity since these become more restricted in the former and greater in the latter with increased estuarine evolution.

The estuarine reaches of the Snowy and Brodribb rivers can be further divided into sub-environments (shown in Fig. 4) with distinguishing morphologies, sediments and processes operating within them:

(a) Tidal delta—the lowest reach of the estuary, comprising the entrance and the area adjacent to it is occupied by a small flood tidal delta. This consists of marine/nearshore sand pushed into the

Sample No.	Location and distance (km)	Description[A]	Size[B]	Sorting	Angularity	Comments
S89/1	Lagoon (0.3)	sl. muddy sand	m–c	well	subang. to subround	
S89/2	Snowy tidal delta (0.1)	clean sand	m	v. well	rounded	shelly marine sand
S89/3	Snowy (1.2)	sl. sandy organic rich mud	m	v. well	ang. to subang.	possibly fluvial sand + tidal mud
S89/4	Snowy (2.3)	sl. muddy sand	m–<u>c</u>	mod.	ang. to subang.	re-worked fluvial sand, finer on top; shell frags
S89/5	Snowy (2.3)	sl. muddy sand	m–<u>c</u>	mod. to poor	ang. to subang.	re-worked fluvial sand, angular shell frags
S89/6	Snowy (3.3)	sl. muddy sand	m–c	poor	ang.	whole estuarine shells
S89/7	Corringle Ck (4.2)	sl. muddy sand	f–<u>m</u>	poor	ang.	mica, fluvial mud
S89/8	Corringle Ck (4.1)	sl. muddy sand	m–<u>vc</u>	v. poor–poor	ang.	tidal mud over fluvial sand, little re-working
S89/9	Snowy (4.3)	muddy sand	m–<u>c</u>–vc	poor	ang.	2 populations fluvial sand
S89/10	Snowy (6.0)	sand, trace mud	m–<u>c</u>	mod.	ang.	mica, charcoal
S89/11	Snowy (7.1)	clean sand	m–<u>c</u>–vc	poor	ang.	mica, charcoal, leaves
S89/12	Snowy (8.5)	clean sand	m–<u>c</u>–vc	mod.	ang.	mica, charcoal
S89/13	Snowy (4.0)	sand, trace mud	m–<u>c</u>–vc	mod.	ang.	mica, charcoal, re-worked river sand
S89/14	Brodribb (5.6)	sl. muddy sand	m–<u>c</u>–vc	poor	ang.	mica, charcoal, whole bivalves
S89/15	Brodribb (6.5)	sl. muddy sand	m–<u>c</u>–vc	poor	ang.	mica, charcoal, coarse frags estuarine shells
SE93/4/8	Brodribb (8.9)	sl. muddy sand	c	mod.	subround	
SE93/4/10	Brodribb (10.7)	sl. muddy sand	c	mod.	subang.	
SE93/4/13	mouth of L. Curlip (13.0)	muddy sand	c	mod.	subround	
SE93/4/18	mouth of L. Corringle (4.7)	sand	c	good		

Table 2. Bed sediment samples (source: 1989 HWMP; 1993 unpub. reports, Monash University). [A]sl. = slightly; [B]f = fine (2.25 to 1.75 phi), m = medium (1.5 to 1.25 phi), c = coarse (1 to 0.25 phi), vc = very coarse (0 to −0.5 phi), <u>underline</u> indicates dominant size fraction.

estuary by tidal currents with wave modification of deposits occurring near the mouth. Transport of sand into the estuary is limited as the tidal currents enter the wider section and the tidal delta occupies only a small area adjacent to the mouth.

(b) Mud basin—a small section of the estuary between the tidal delta and First Island is characterised by a relatively wide, deeper segment with finer sediments. This area is acting as a sediment sink for marine sediment at its downstream end and for finer fluvial sediments from upstream. Larger fluvial events would carry coarser sediment through this section but higher frequency flows of smaller magnitude do not seem to transport appreciable amounts of sand-sized material to this zone.

(c) Tidal channels—these are located in the sinuous sections of channel from First Island upstream to Lake Corringle and approximately the confluence of the Little Snowy with the Snowy and Brodribb rivers. The basic morphology is produced by a combination of fluvial and tidal processes. Sediments in this area are primarily composed of fluvial sand with varying percentages of mud, much of which is probably deposited over the sands during periods when tidal currents dominate the circulation. The fluvial sand would be transported to this zone during floods, and then re-worked by tidal currents.

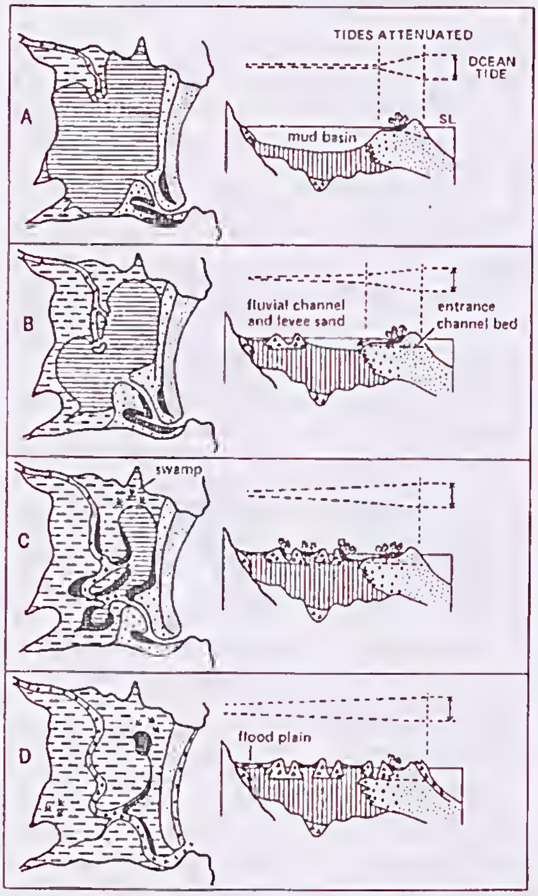

Fig. 3. Stages of infilling of Roy's Type 4 barrier estuary (after Roy 1984).

(d) Lakes—these broad, shallow environments have largely wind-driven circulation and sediments are predominantly muds. Tidal currents are negligible in the body of the lakes.

(e) Tidal river channels—these upper-estuarine zones are characterised by fluvial sands with the basic morphology being controlled by riverine processes. The tidal effects vary between the Snowy and Brodribb, largely as a result of the considerable tidal storage in Lake Curlip, some distance upstream on the Brodribb. This provides for significant tidal velocities over the reach connecting the lake to the lower Snowy River. The Snowy River tidal prism decreases more rapidly upstream and tidal velocities capable of re-working sand-sized sediment are restricted to its lower reach.

SNOWY RIVER ESTUARY: HYDRODYNAMICS

The hydrodynamic regime is considered below under the headings low, fresh and flood flows. The range of conditions documented from field studies was extended by the use of an hydrodynamic model. Details of the physical basis of the model, its verification and application are given by Hinwood & McLean (1992).

Dry-weather flow conditions

Under dry-weather flow conditions the Snowy River remains the dominant fresh water inflow, although the flow in the Brodribb is not negligible in determining the salinity distribution. The ungauged Corringle Creek drains a small lowland catchment but may also contribute following coastal rainfall.

Since the Snowy Mountains Scheme, the median flow has fallen to 1051 ML/day. The 'environmental flow' of significance to water quality and maintenance of ecosystems has been provisionally assessed as 225 ML/day (James 1989)—occurring as the lowest average 7-day flow. The 7-day low flow falls below this value once in every 2.6 years on average.

As noted earlier, under low flow conditions a salt wedge forms in the Snowy River upstream of its junction with the Brodribb (see Fig. 5). The extent of the salt wedge is reduced from that in an unbranched channel by the low salinity of the saline water at the start of the salt wedge near km 5. The low fresh inflows mean that salt wedges rarely form in the Brodribb River or Corringle Creek. Flows in these estuarine channels are well mixed vertically by the tides, except near slack water. This situation is shown by the time–depth plots of salinity in Fig. 6A–B. Near high and low water slack weak stratifications develop in Corringle Creek. A sharp stratification develops near high water slack in the Brodribb River and is only broken up when the ebb current becomes sufficiently strong. The figures are based on temperature/salinity/velocity data measured at about 40 minute intervals on each of three verticals at the given cross-sections; data were measured at 0.5 m intervals with finer sampling near sharp interfaces.

The water entering Brodribb River and Corringle Creek from the Snowy River estuary on the flood tide may be stratified and will vary in salinity over the tide cycle. Mixing by tidally-generated turbulence will break up the vertical stratification, and dispersion will reduce the longitudinal variations. Wind mixing in the lakes observed during the data collection in January 1989 and in 1993 caused thorough vertical mixing and stirred up bottom sediment, increasing turbidity particularly in Lake Corringle. The water re-entering the Snowy River estuary on the ebb tide will thus have different properties to that in the estuary and will produce a complex and rapidly varying salinity distribution. This situation is illustrated in Fig. 7A–B.

Fig. 7A shows dramatic changes of salinity and of flow regime at a point in the Snowy River just upstream of the junction with the Brodribb. A salt wedge is present for most of the ebb tide. The wedge had been pushed upstream by the flood tide but on the ebb it moved downstream at least as far as the junction with the Brodribb River. Serial velocity data at each cross-section confirmed this interpretation.

In the lower estuary, just upstream of Marlo, Fig. 7B shows that a number of interfaces passed the observation station during a tide cycle. In this

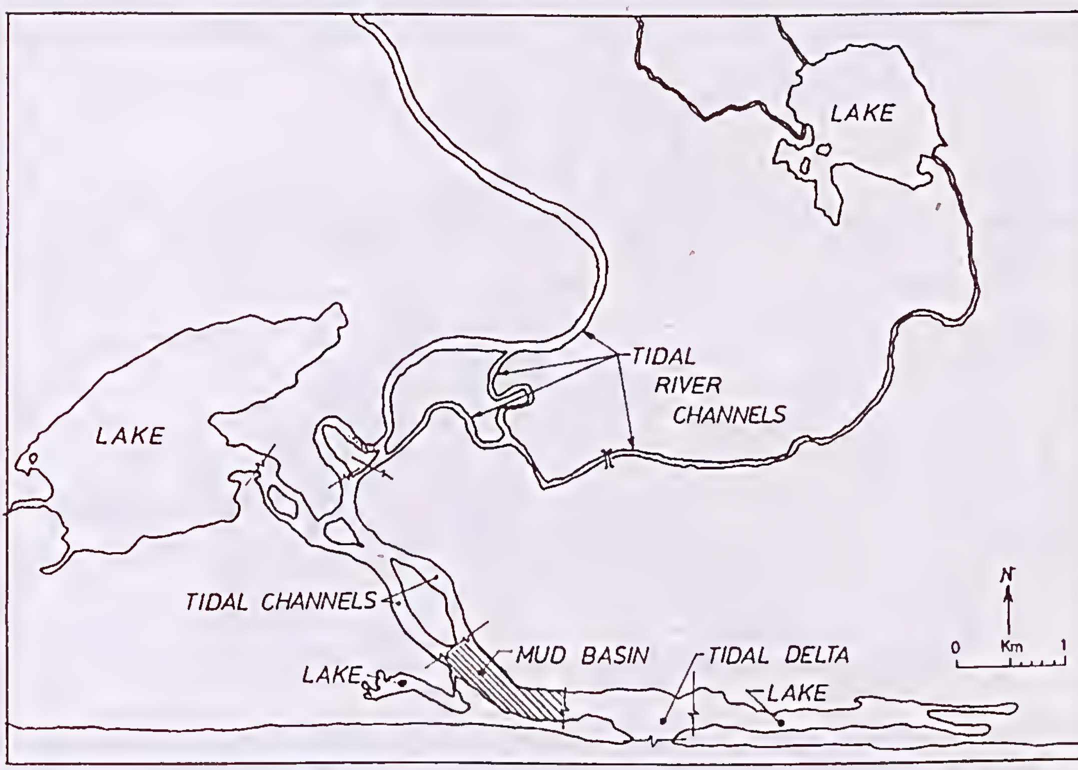

Fig. 4. Morphological zones within the Snowy River estuary.

reach the advancing flood current halted the outflow of fresh water and formed a fresh wedge at the water surface. The tip of the wedge was marked by a sharp change in water color and turbidity. The tip of the fresh wedge was pushed upstream and just reached the measurement station at high water slack.

The field study was conducted in January 1989 not long after a flood which peaked at 154 000 ML/day on 17 November 1988. The tidal range of 0.7 m at Marlo is typical after a fresh or flood, but falls with time as longshore drift obstructs the inlet. The salt wedge will penetrate slightly less far upstream at high water with the higher tide, as explained below.

Under higher river flow conditions observed over the period 18–20 September 1998, the salt wedge was washed downstream and the top to bottom salinity difference was greatly reduced. On 19 September the flow in the Snowy was 1900 ML/day, the tidal range at Marlo was 0.7 m and the maximum upstream extent of the salt wedge was 6.2 km.

Fresh conditions

Minor fresh flows are sufficient to wash the salt wedge out of the Snowy River above its confluence with the Brodribb and to establish a salt wedge regime in the lower estuary near Marlo, as shown by the data of 18–21 September 1992. With a tidal range at Marlo of 0.49 m and a flow in the Snowy of 6900 ML/day, in the Brodribb of 2600 ML/day and Corringle Creek of 900 ML/day on 19 September, the salt wedge length was about 3 km, ie. near the tip of First Island. The combined river flow is then relevant to the salt wedge dynamics.

Minor fresh flows are of frequent occurrence and may last for a couple of days or more. The upper limit of a 'fresh' is taken as the bankfull flow in the Snowy, and is about 17 020 ML/day. Such a flow will occur or be exceeded one day per month on average.

Numerical model runs shown in Fig. 8 confirmed that for flows in the Snowy River above about 2750 ML/day, sustained for a few days, the salt wedge is washed out of the Snowy River above its confluence with the Brodribb. Under intermediate flows, a salt wedge extends upstream from the mud basin towards the confluence. For combined inflows of all rivers more than about 25 000 ML/day (17 020 ML/day in the Snowy) salt water does not penetrate past the inlet throat, again depending on tidal range and state of scour of the inlet. The model runs utilised a typical tidal

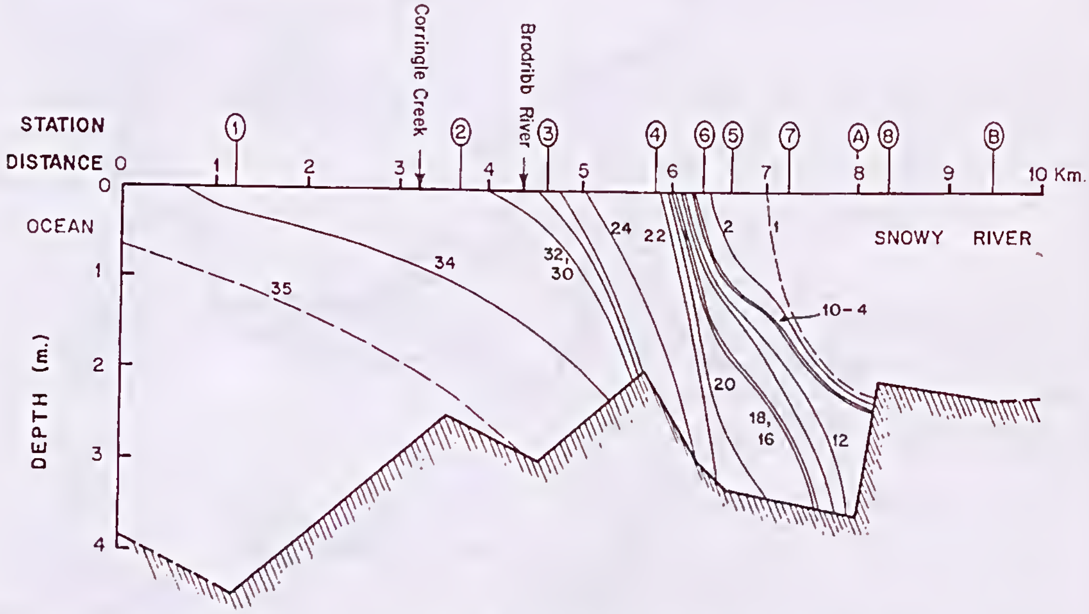

Fig. 5. Salinity contours showing a salt wedge in the Snowy River estuary under dry-weather river flows, indicated by the concentration of salinity contours from km 5.8 to km 8.1. Near high water, 1200–1400 hours, 11 January 1989. Circled numbers and letters refer to TS profiling stations; contour levels are salinity in ppt.

range of 0.5 m and assumed that the river inflows were in the ratio Snowy : Brodribb : Corringle = 1 : 0.75 : 0.0375.

Higher tidal ranges will increase mixing and by disrupting the density stratification will reduce the upstream penetration of the salt wedge—eg. for a tidal range of 0.6 m a flow in the Snowy of 2500 ML/day is sufficient to flush the salt wedge from the upper river. The limiting flow also depends on the flow in the Brodribb River through its effect on the salinity at the confluence.

Numerical model runs were made for several transient fresh flow scenarios, one of which is illustrated in Hinwood & McLean (1992). The scenarios used Snowy River inflows rising over 2 to 4 days to maxima of 12 000 to 25 000 ML/day and then falling over 4 to 8 days. The model showed that for these river flows and durations salt water will be flushed from the Snowy River channels, but the Lagoon will remain saline and Lake Curlip and the Brodribb River will not be completely flushed, whereas a steady combined river inflow of 25 000 ML/day will flush salt water from the estuary.

Flood conditions

Unpublished data in the files of the Rural Water Commission shows that for floods of up to 14 000 ML/day the flow in the lower Snowy River remains entirely within the channel. In greater floods outflows occur via gulches near Orbost and low-lying areas of the flood plain are inundated, but the bulk of the flow remains within the channel. For flows above 40 000 ML/day overflows from the Snowy River flow into the Lake Curlip area. Flows in the Snowy above 40 000 ML/day occur on average 4 days each year. The overland flow is intercepted by the Brodribb River. This river rises above bankfull during the larger floods on the Snowy River and inundates areas on both sides of its channel.

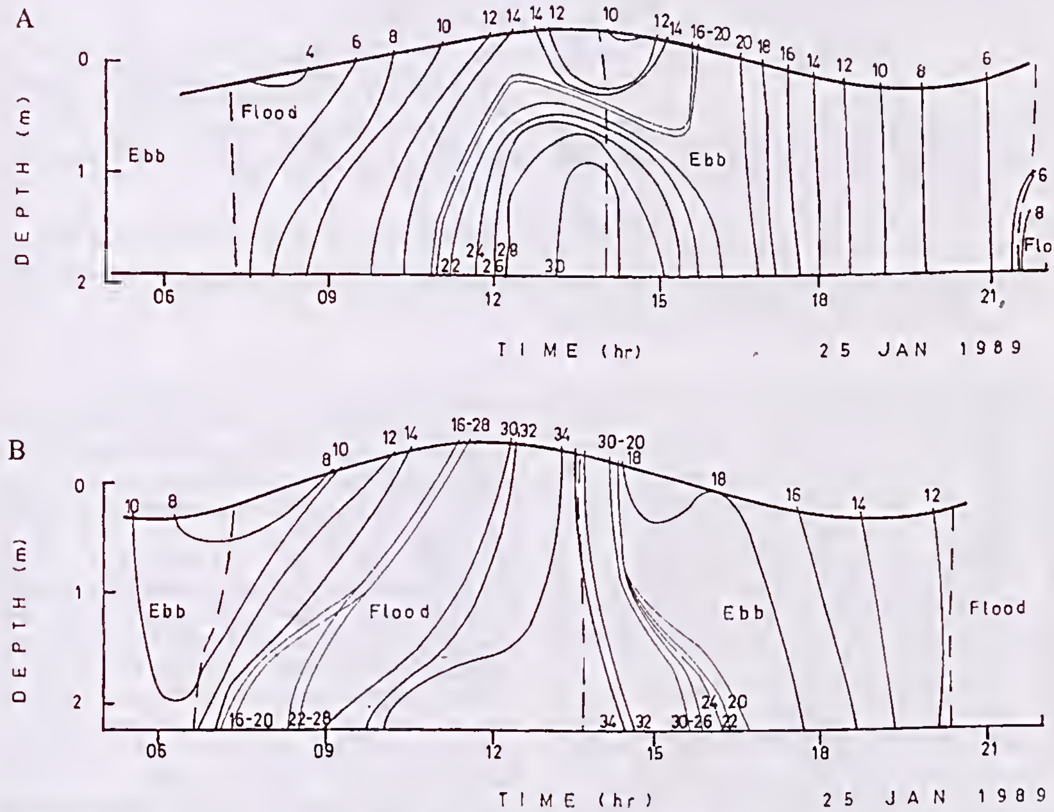

Fig. 6. Salinity contours on a depth-time plot. Numbers are salinity in ppt; broken lines denote zero velocity. A, Corringle Creek, stn 2; B, Brodribb River, stn 4.

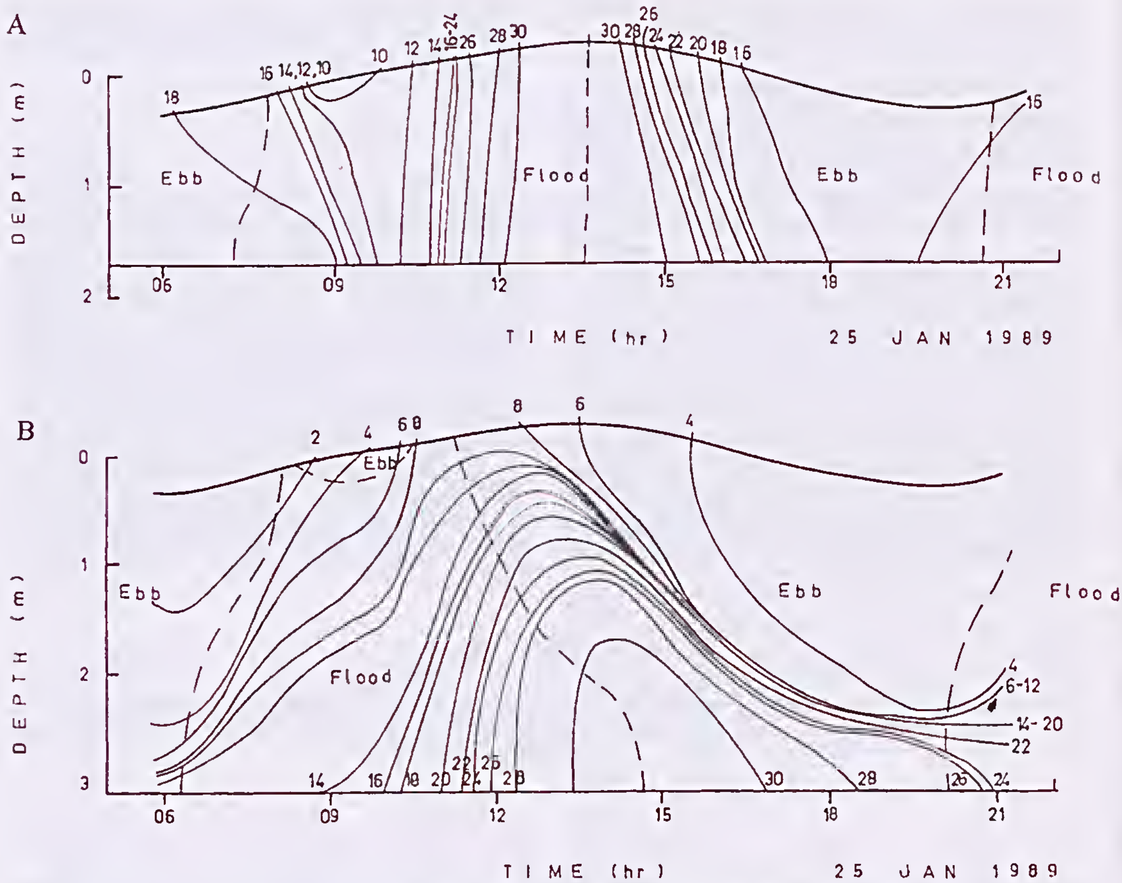

Fig. 7. Salinity contours on a depth–time plot. Numbers are salinity in ppt; broken lines denote zero velocity. A, Snowy River, stn 3; B, Snowy River, stn 1.

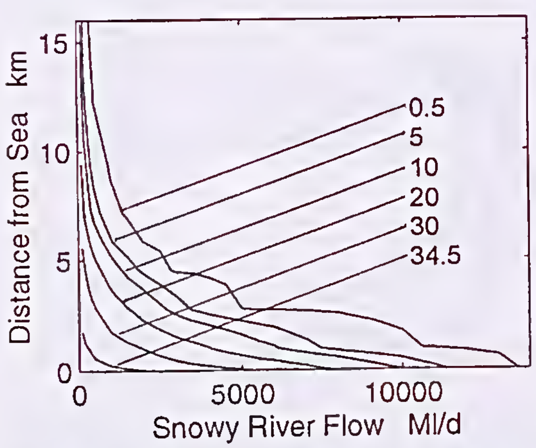

Fig. 8. Snowy River—salinity at high water as a function of river flow. Tidal range at Marlo = 0.5 m.

Under high fresh conditions observed over the period 17–19 September 1993 no sea water, or extensive body of salt water was found in the lower estuary under a combined river inflow of 22 000–24 000 ML/day. Saline water of 5–10 ppt was found near the bed at the ends of The Slips, the Lagoon and in Lake Corringle. Water of up to 5 ppt was found near the channel bed and this could loosely be termed a salt wedge, confirming the model estimate of 25 000 ML/day as the flow required to flush the salt wedge out of the estuary.

For a bankfull flood in the Snowy River, the sectionally-averaged current velocities through the mud basin reach 0.9 m/s and through the entrance gorge reach 1.8 m/s. This latter figure is well over twice the speed derived from the equilibrium gorge equation of O'Brien (1931). No allowance for scour during a flood has been made but it is evident that scour would occur, increasing section areas and thereby reducing current speeds. Salt water is entirely flushed out of the Snowy River and Lake Corringle, but for a bankfull flood of typically short duration, a trace of salt water remains in Lake Curlip.

Bankfull flow for the estuarine section of the Brodribb River is estimated by the authors as 16 000 ML/day (±30% due mainly to uncertainty in the water surface slope). This flow is reached due to flooding of the Brodribb alone once in 8.5 years.

Overview and estuarine zones

In summary, under flood and high fresh flows salt water is flushed from the estuary. Under low flows, salt water penetrates up the Snowy River and its estuarine tributaries, the Brodribb River and Corringle Creek.

The entrance of the estuary to the sea is through a barrier dune. The entrance gradually moves eastward and is closed by longshore sand drift. Freshes scour the channel and entrance. Floods scour the channels and may cut the barrier dune, moving the entrance westwards. A barrier lagoon is formed to the east when the entrance is moved westwards; this lagoon is gradually returned to an estuarine channel as the entrance moves eastwards. The entrance has closed on only two occasions in 80 years.

At low river flows tidal velocities dominate in the lower estuary. Following a flood or fresh the entrance area is large and the tidal range is large, but the range falls as the entrance moves east and contracts.

On hydraulic grounds a number of zones may be identified within the estuary under low flow conditions. Under flood flows the salt water is washed out and the importance of the tides reduced, converting most zones to river channel segments. The zones are discussed below.

Eastern Lagoon and The Slips. These are elongated lagoons formed from abandoned river channel lying parallel to the coastline. Velocities are typically less than 0.2 m/s and stirring by wave or current action is weak. Lying close to the entrance the salinity is close to that of seawater over the whole tide cycle.

Flood tide delta. The flood tide delta from the mouth of the estuary to about km 0.8 is subjected to strong tidal currents, sufficient to cause appreciable bedload transport of sand. Under dry-weather and fresh river inflows the water near the bed is always seawater, while on the ebb tide a shallow surface layer of fresher water intrudes from upstream and flows out to sea.

Mud basin. This section of the estuary upstream of the flood tide delta, near Marlo, is characterised by a wide deep channel. The bed is not exposed to strong currents or stirring by wind waves. At times of dry-weather river inflow the lower layers of water remain nearly undiluted seawater and the upper layers vary over the tide cycle from seawater to two-thirds river water.

Snowy River tidal channels. From the mud basin to a little above the confluence with the Brodribb River the currents in the Snowy River are predominantly tidal, except during floods. The strength of the tidal currents and the salinity of the water near the bed are very strongly influenced by the tidal flows in the Brodribb River and Corringle Creek. Under dry-weather river inflow conditions the salinity near the bed varies over a tide cycle from nearly seawater to two-thirds river water. Under moderate fresh flows the salt wedge is pushed downstream to this reach.

Salt wedge zone. This subsection of the Snowy River tidal channel extends from about km 5 to km 8 and on occasion upstream of km 10. Under the median or dry-weather river inflows a salt wedge forms here with river water overlying mixed water of about one part seawater to two parts river water. Currents remain predominantly tidal but modified by net outflow near the surface and net inflow near the bed due to the salt wedge.

Snowy River tidal river channel. Currents are tidal, but weak and insufficient to transport sand under dry-weather river inflows, but moderate fresh flows dominate when present. Upstream of the salt wedge zone the bed is only rarely exposed to saline water. Rare incursions of brackish water are stated to occur at least as far upstream as Orbost under very low flow conditions when water levels are raised by closure or extreme constriction of the entrance channel. These conditions are stagnant.

Brodribb River and Corringle Creek tidal channels. Under dry-weather flows these channels are dominated by tidal currents which are sufficiently strong to mix the water over the depth, except near slack water. The salinities are intermediate between seawater and river water, decreasing upstream.

Lakes Corringle and Curlip. These remnants of the estuarine embayment are strongly tidal but currents are weak except near their entrances or during strong wind events. Even in dry weather the small river inflows are sufficient to lower the salinity within the lakes, producing horizontal salinity gradients. The lakes, being shallow and well mixed vertically by the wind, are readily flushed by fresh flows in the Brodribb River and from the western marshes respectively. Flushing from freshes in the Snowy River takes about one week because of the extent of the lakes and the length of the channels linking them to the Snowy River.

SNOWY RIVER ESTUARY: BENTHIC ECOLOGY

A reconnaissance survey of the intertidal and subtidal habitats in the Snowy River estuary was made and is reported in HWMP. Methods comprised visual assessment; sampling of vegetation, sediments and infauna; laboratory examination and broad classification of sediments and of biota. Transects were sampled at km 0.5, km 1.3, km 1.9 and point samples gathered at km 7.0 and at km 0.3 in the mouth of the Lagoon (see Fig. 1). This sampling, as described in HWMP, identified as ecological zones the flood tide delta, a second zone upstream with more diversity of marine/estuarine invertebrates and the marine backwater of the Lagoon.

DETAILED CLASSIFICATION OF THE SNOWY RIVER

The detailed classification of the Snowy River estuary is discussed below. From this, Fig. 9 has been prepared to show in schematic form the characteristic salinity variation for an estuary of this type and stage of evolution.

Hydrodynamics

The Snowy River estuary has a wide range of the 'classical' hydrodynamic regimes present simultaneously. Starting upstream with the river channel:

- unstratified (fresh);
- salt wedge;
- partially mixed, with strong tidal currents mixed;
- partially mixed tidally dominated; and
- mixed, with limited wave penetration.

It is believed that this pattern is typical of most estuaries in this stage of geomorphological evolution. Among estuaries in this region, the same sequence has been observed by the authors in the Barwon, Werribee and Pambula River estuaries, and an extensive data collection by CSIRO (Rochford 1959) documented varying patterns of flow along NSW river-dominated estuaries where different flow characteristics were produced by the interaction of tide and river flow in the different geomorphological zones of the estuary.

The pattern of salinity regimes is shown in Fig. 9. The channel morphology has been used to characterise each zone, then the other characteristics observed on the Snowy River have been listed for each zone. The salinity graphs have been obtained from runs of the model; the abscissa has been distorted to fit the dimensions of the columns of the figure.

In both the Brodribb River and Corringle Creek the sequence is the same as in the Snowy River but the relative lengths of the zones are different. The smaller fresh inflows and larger tidal prisms make the zone with mixed/partially mixed with strong tidal currents longer, and the salt wedge zone shorter in the Brodribb.

In the Snowy River low flows occur for most of the year but fresh flows may occur at any time of year and are of short duration. With the large tidal lagoons typical of this type of estuary, the estuary responds fairly slowly to the fresh flows, attenuating the changes, hence the impact of fresh flows is diminished. An estuary in a later stage of evolution, with less tidal lagoon area, or an estuary fed by a less variable stream would adjust fully to the changes in river flow.

Sediments

In the Snowy River, with mostly sandy sediments, flood conditions are more important for sediment transport than fresh or dry-weather flows as a consequence of the generally subcritical current speeds under the latter conditions. Under flood conditions the salt wedge is washed out and the direction of bed sediment transport is therefore downstream in all reaches of the estuary, the flood delta scours and the barrier dune may be breached. In the falling stages of a flood the fines would be deposited in the mud basin and lower tidal channels. The upstream-moving water in the salt wedge would carry the consolidating flocculated silt landwards into the upper tidal channels and the tidal lagoons, as has been well documented for many estuaries.

Under conditions of lower flow, redistribution of sand in the tidal river channels will occur through the action of the tidal currents, the currents in the salt wedge being too weak to move sand. The inflow of marine sands onto the flood tide delta will resume. Silt will be resuspended in the shallow lagoons by strong wind waves and will then be transported by the currents.

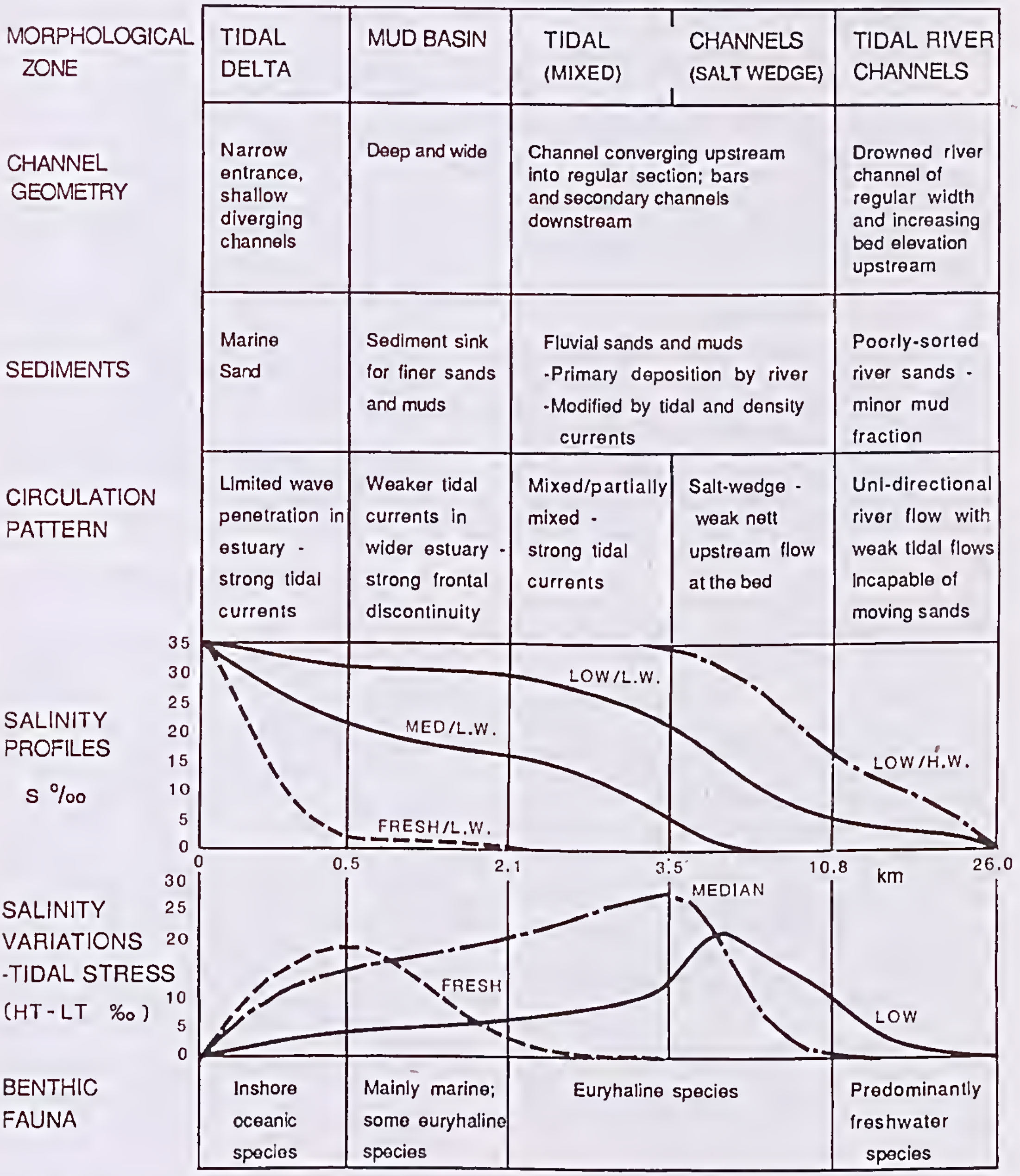

Fig. 9. Snowy River—morphological zones and typical salinity ranges for low and moderate fresh flows. 7 day low: Snowy flow 225 ML/day; median Snowy flow 1051 ML/day; fresh Snowy flow 17 000 ML/day. Tidal range at Marlo = 0.6 m. Annotation on salinity profiles: flow/tide. L.W. = low water; H.W. = high water.

Habitat

The biota present have been found to correlate well with the morphological zones. These zones define the channel depth, the bed sediment type and the hydrodynamic regime. Considering the hydrodynamics, it is clear that the average salinity decreases upstream, but the tidal range of salinity, here referred to as the tidal stress, varies depending on the regime. Fig. 9 shows that the tidal stress is a maximum at the downstream end of the salt wedge, and a minimum in the mud basin and flood tide delta, where predominantly marine benthos have been observed. The seasonal salinity stress may be inferred from the upper and lower lines on the salinity variation plot, remembering that the exposure to the minimum salinity may be brief.

CONCLUSIONS

The Snowy River estuary is the largely infilled remnant of a shallow embayment, receiving substantial fresh water and sediment inflows from the catchment. The present estuary channels and mouth are formed by floods of return period 5 or more years, with limited re-working by tidal currents. Longshore drift gradually closes the entrance, reducing the tidal prism and restricting the ingress of salt water. Channel sediments are predominantly fluvial sands, with some marine sands on and seawards of the flood tide delta, and silts in the tidal lagoons. Zones with characteristic geomorphological regimes were defined.

Maximum salt penetration into the estuary occurs under conditions of low river inflow and large entrance depth. The data reported here, gathered under these conditions, identified a range of hydrodynamic and salinity regimes present in the estuary, from well mixed to salt wedge types. The range of conditions was extended by use of a numerical model. The mix of hydrodynamic regimes along the Snowy River estuary indicates the limited utility of purely hydrodynamic classification schemes when applied to a whole estuary. The relationship between the biota present and the hydrodynamic and geomorphological zones has been demonstrated.

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Findings by Dr J. E. Watson reported in HWMP, based on marine benthic faunal data, have been used.

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